ALL-OPTICAL DATA REGENERATION BASED ON SELF-PHASE MODULATION EFFECT

P.V. Mamyshev

Bell Laboratories - Lucent Technologies Holmdel, NJ 07733 (pavel@bell-labs.com)

Abstract: A simple all-optical regeneration technique is described. The regenerator suppresses the noise in "zeros" and the amplitude fluctuations in "ones" of return-to-zero optical data streams. Numerical simulations and experimental results are presented.

Introduction

Whenever an optical data signal is generated, transmitted, switched etc., the signal usually gets distorted. The distortion accumulates with the transmission distance and/or with the number of processes (switching, demultiplexing etc.) made with the data. In order to avoid severe degradation of the signal, one can put one or more regenerators in the system. The purpose of the regenerators is to restore the quality of the signal. For many reasons, one would like to avoid using high-speed electronics in the data regeneration. In this paper, a simple all-optical regeneration technique is presented. The method suppresses the noise in "zeros" and the amplitude fluctuations in "ones" of return-to-zero (RZ) optical data streams. The method is based on the effect of self-phase modulation (SPM) of the data signal in a nonlinear medium with a subsequent optical filtering at a frequency ω_f which is shifted with respect to the input data carrier frequency ω_0. The output pulses are close to transform-limited, and the resultant transfer function (output pulse intensity versus input pulse intensity) is close to a binary one. SPM can be performed in a fiber (which can be a part of the transmission line) or in any other nonlinear material.

Description of the idea and numerical simulations

Qualitatively, the idea of the method is as follows (Fig.1). The input pulses (that have to be regenerated) have a spectral bandwidth $\Delta\omega_0 \sim 1/\tau$ (τ - pulsewidth). Due to the effect of SPM, the spectral bandwidth of the pulses broadens:

$$\Delta\omega_{SPM} = \Delta\omega_0 (2\pi/\lambda) n_2 I_p L \qquad (1)$$

Where I_p is the pulse intensity (which can be different for different pulses), n_2 is the nonlinear refractive index, λ is the wavelength, L is the length of the nonlinear medium. After the nonlinear medium, the pulses pass through the optical filter, whose center frequency, ω_f, is shifted with respect to the input signal carrier frequency, ω_0:

$$\omega_f = \omega_0 + \Delta\omega_{shift} \qquad (2)$$

If the spectral broadening (1) of a pulse is small enough, i.e. when

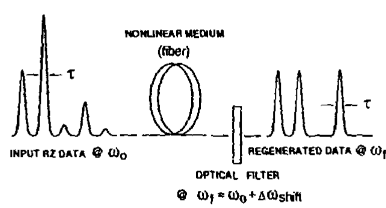
$$\omega_{SPM}/2 < \Delta\omega_{shift}, \qquad (3)$$

the pulse is rejected by the filter. This happens when the pulse intensity I_p is too small (noise in "zeros"). If the pulse intensity is high enough so that

$$\omega_{SPM}/2 \geq \Delta\omega_{shift}, \qquad (4)$$

a part of the SPM-broadened spectrum passes through the filter. The spectral bandwidth of the filtered pulse is determined by the filter spectral bandwidth $\Delta\omega_f$. It is

Fig. 1: Schematic diagram of the regenerator.



important to note that, as it will be shown later, for a wide range of parameters, in the time domain the filtered pulse is essentially a transform-limited pulse. By changing the filter spectral bandwidth $\Delta\omega_f$, one can change the output pulsewidth. (In particular, note that if $\Delta\omega_f \sim \Delta\omega_0$, the output pulsewidth is the same as the input pulsewidth). The intensity of the output pulse after the spectral filtering is proportional to the spectral density of the SPM-broadened spectrum at the output of the nonlinear medium, $I_\omega \equiv dI/d\omega$. From (1) one can estimate:

$$I_\omega \sim I_p / \Delta\omega_{SPM} = \lambda / (\Delta\omega_0 2\pi\, n_2 L) \qquad (5)$$

As one can see, I_ω and, consequently, the intensity of the output pulse are independent of the input pulse intensity I_p (if I_p is high enough so that (4) is met). As a result, we can establish the pulse transfer function (output pulse intensity vs input pulse intensity) of the regenerator of Fig.1:

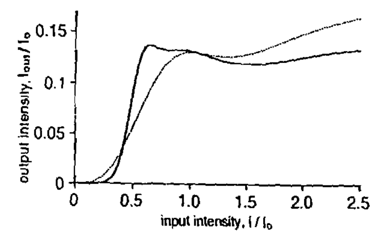
$$I_{out} = 0, \quad if \quad I_p < I_{CR} \qquad (6a)$$
$$I_{out} = const, \quad if \quad I_p > I_{CR} \qquad (6b)$$

where the critical pulse intensity I_{CR} is determined from $\Delta\omega_{SPM}(I_{CR})/2 = \Delta\omega_{shift}$:

$$I_{CR} = \frac{2\Delta\omega_{shift}}{\Delta\omega_0 (2\pi/\lambda) n_2 L} \qquad (7)$$

The transfer function (6) is the ideal transfer function for a regenerator: it shows that the noise in "zeros" is removed (6a) and the amplitude fluctuations in "ones" is suppressed (6b). Let us consider a numerical example. Let the nonlinear material be silica fiber with $n_2 = 2.6\,10^{-16} cm^2/W$, of length $L = 15\ km$, and let λ=1.55 μm and $\Delta\omega_{shift}/\Delta\omega_0 = 2.38$. In this case the critical pulse intensity is $I_{CR} = 3\,10^5 W/cm^2$, and for a fiber with effective core area $35\ \mu m^2$, the corresponding pulse peak power is 100 mW. For a data stream with a period-to pulse duration ratio of $T/\tau = 5$, the corresponding average data signal power is 10 mW. The normal operating condition should be a few times higher than this critical value, so that $P_{data,ave} \sim 30-40\,mW$. Note that the average signal power does not depend on the data bit-rate. When the regenerator is used in systems where spectrally broad noise is accumulated, one may need to put another optical filter centered at the signal frequency ω_0 at the input of the regenerator, in order to suppress the noise outside the signal spectrum.

Fig. 2: Transfer functions of single-stage (dashed curve) and two-stage (solid curve) regenerators).

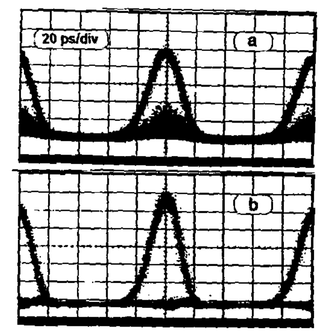


In the above qualitative explanation of the method, we did not specify the value and sign of the dispersion of the nonlinear material (fiber, for example). The method can work with zero and nonzero (positive or negative) dispersion. Nevertheless, a small negative (non-soliton) dispersion $D < 0$ can be preferable, because it this case the SPM-broadened pulse spectra have a more "flat-top" rectangular shape, which, in turn, leads to a flatter transfer function for $I_p > I_{CR}$. Fig.2 shows results of numerical simulations for the case of negative D. The parameters are: $z_{NL}/z_D = 0.015$; $L/z_{NL} = 12$; spectral bandwidth (FWHM) of the Gaussian filter $\Delta\omega_f/2\pi = 0.45/\tau$; $\Delta\omega_{shift}\tau/2\pi = 1$; the dispersion length $z_D \equiv 2\pi c 0.322\tau^2/(\lambda^2|D|)$; and the nonlinear length $z_{NL} \equiv (n_2 I_0 2\pi/\lambda)^{-1}$. Here I_0 is a normalization pulse peak intensity, $I_0 = 2.5 I_{CR}$ in this particular example. The resultant transfer function of the regenerator is close to ideal (Fig.2, dashed curve). The regenerated pulses have close to Gaussian shape (the pulse shape can be changed by changing the filter shape). The bandwidth of the filter in this example is chosen so that the width of the regenerated pulses is essentially the same as that of the input pulses. It is also important to note that the time position variation of the regenerated pulses, induced by the input pulse intensity fluctuations, is small (less than ± 10% of τ). Note that if the wavelength offset of the regenerated data with respect to the input data is undesirable for some applications, one can use two regenerators in series, having the same magnitudes but opposite signs of the frequency offsets $\Delta\omega_{shift1} = -\Delta\omega_{shift2}$, so that the net offset is zero. As one would expect, the performance characteristics of the two-stage regeneration are even better than those of a single-stage. In particular, the transfer function becomes essentially ideal (Fig.2, solid curve).

Experimental results

To demonstrate the effectiveness of the regenerator, the following model experiment was performed. A modulator with a very poor on/off ratio was used to impose the data on a 10 GHz pulse stream. The resultant eye diagram of the optical data stream was partially closed, it is shown on Fig.3a. In the regenerator, a fiber of length L=8 km with

Fig. 3: Eye diagrams before (a) and after (b) theall-optical regeneration



the effective mode area 45 μm² and the negative dispersion D=-2ps/nm-km at 1.55μm was used. The average power at the fiber input was 90 mW. The output filter had the bandwidth of $\Delta\omega_f/2\pi$=29GHz (FWHM), and the filter frequency offset with respect to the input signal carrier frequency was $\Delta\omega_{shift}/2\pi$=100 GHz. Fig.3b shows the eye diagram of the signal after the single-stage regeneration. One can see that the eye diagram is completely open now. Note that the output pulses are essentially transform-limited.

One can see how effective this technique is, in particular, in suppressing the signal background. This feature can be very useful, for example, for cleaning up the TDM (time division multiplexing) channels before they are optically multiplexed to a higher bit rate.

The regenerator can be used also as a wavelength converter. It is important to note that the value of the filter frequency offset $\Delta\omega_{shift}$ is not critical to perform a high-quality regeneration. Note also, that one can select not just one (as it is described above) but two or more spectral bands at the output of the nonlinear medium and, thus, get the regenerated signals simultaneously at different wavelengths. It should be emphasised that the regeneration technique should be even easier to implement at higher bit rates, since the filter frequency offset and bandwidth are bigger when shorter pulses are used.